Heavy-duty Vehicle Platooning and Scheduling Swedish Handball

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Background

2012: Ph.D. in Applied Mathematics from University of Colorado Denver

- Dissertation: Derivative-free Optimization of Noisy Functions

2012 - 2014: Postdoctoral Researcher, Department of Automatic Control, KTH Royal Institute of Technology

Present: Postdoctoral Researcher, Mathematics and Computer Science, Argonne National Laboratory

- Heavy-duty Vehicle Platooning
- Sports Scheduling
- Derivative-free Optimization
- Distributed Multi-agent Optimization
- Tiled QR Factorization

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- **Sports Scheduling**
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Outline

Heavy-duty Vehicle Platooning

Sports Scheduling

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Heavy-duty Vehicle Platooning

Sports Scheduling

Problem Statement

Goal

$$\text{minimize Total Fuel Use}$$
$$\text{such that Vehicles Arrive on Time}$$

Using the fact that vehicles travelling in a platoon consume less fuel than when travelling independently

What is a Platoon?

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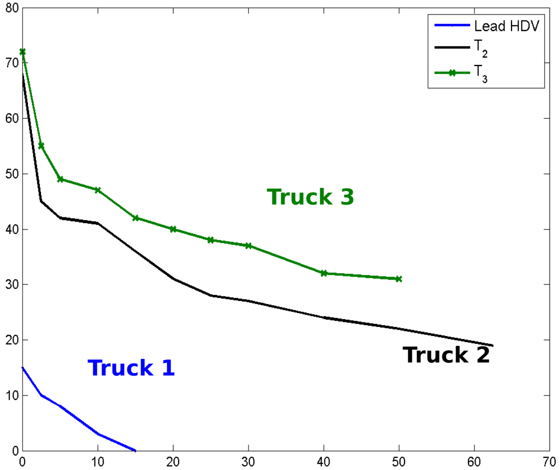
What is a Platoon?

Approximately 30% of an HDV's life costs is fuel.

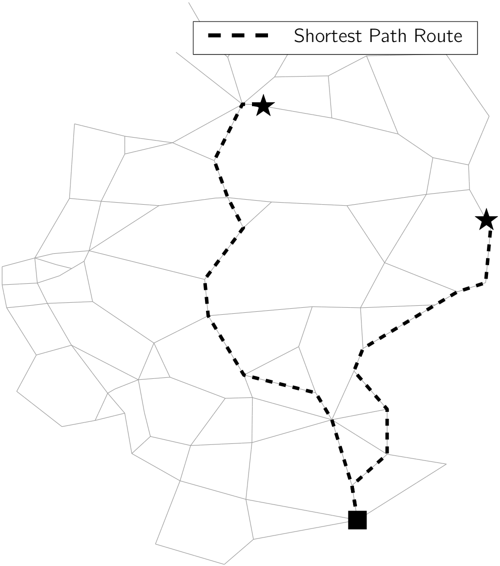
Platooning Fuel Savings



Previous Work

- 1966 – W. Levine and M. Athans, "On the Optimal Error Regulation of a String of Moving Vehicles"
- 1995 – M. Zabat, N. Stabile, S. Farascaroli, F. Browand, "The Aerodynamic Performance Of Platoons" UC Berkeley: California Partners for Advanced Transit and Highways (PATH)
- 2010 – T. Robinson, E. Chan, and E. Coelingh, "Operating Platoons on Public Motorways: An Introduction to the SARTRE Platooning Programme"

Fundamental Concept



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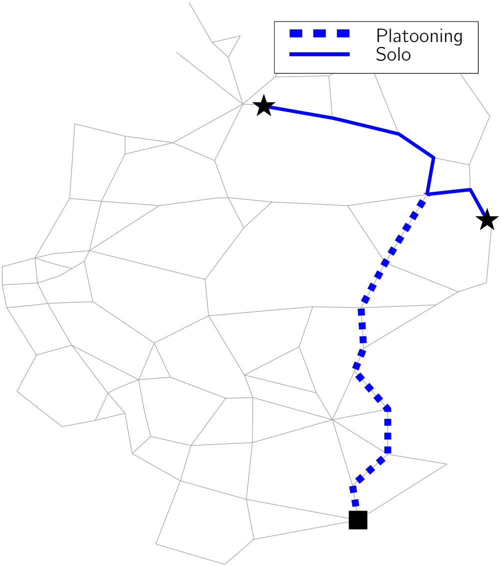
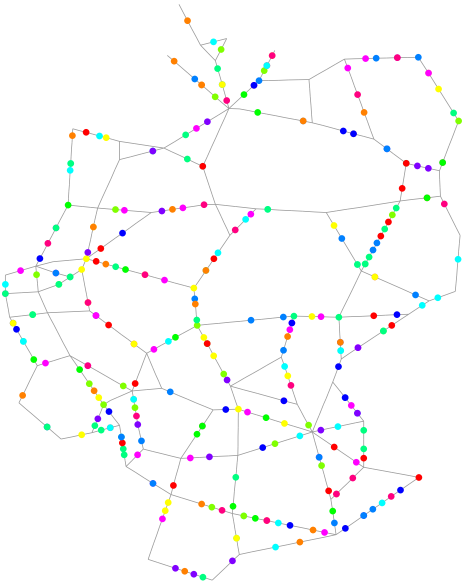
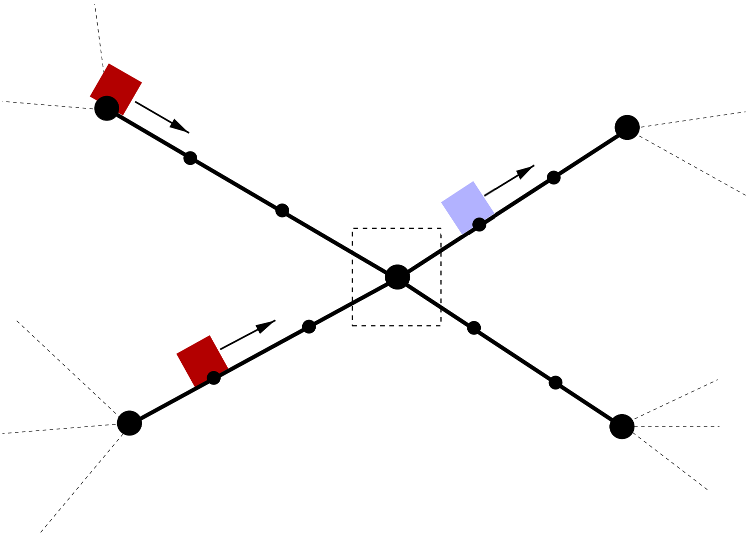


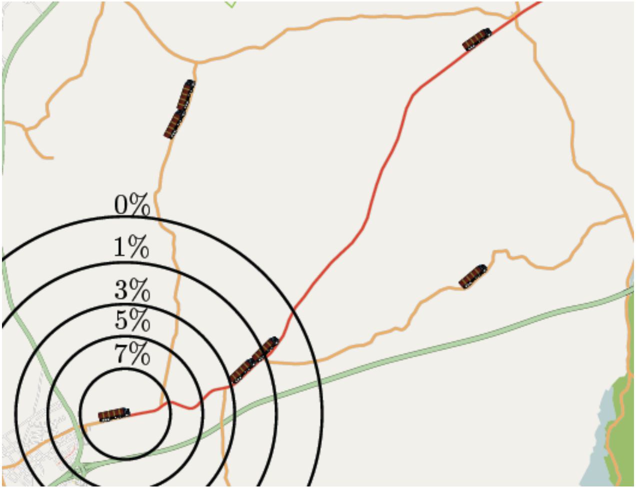
Difficult Problem



Local Controller



Catching Up



Pseudocode

Algorithm: Logic for the local controller

```
if Approaching HDVs can feasibly adjust their speeds to form a platoon then
    if Test of sufficient savings then
        Inform the HDVs to adjust their speeds to form a platoon
    end
end
```

Pseudocode

Algorithm: Logic for the local controller

if *Approaching HDVs can feasibly adjust their speeds to form a platoon* **then**

    if *Test of sufficient savings* **then**

        Inform the HDVs to adjust their speeds to form a platoon

    end

end

Notation:

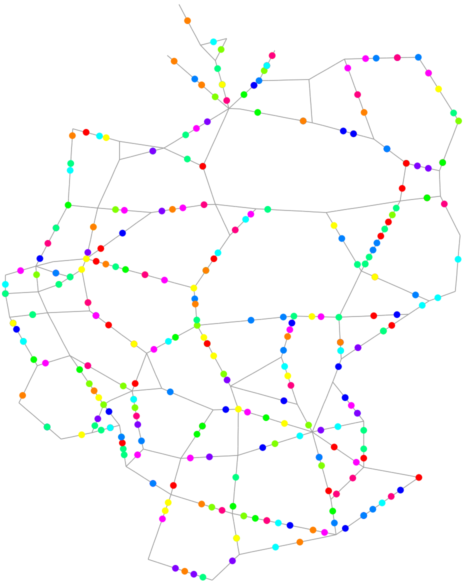
- Represent our network with a graph $G = (V, E)$.
- Denote the control node s and let d_n be the destination for HDV n.
- Let $D(i, j)$ be the fuel used travelling from vertex i to vertex j.
- Let m_n be the allowed detour for HDV n.
- Let η be the percentage of fuel saved by platooning.

Pseudocode

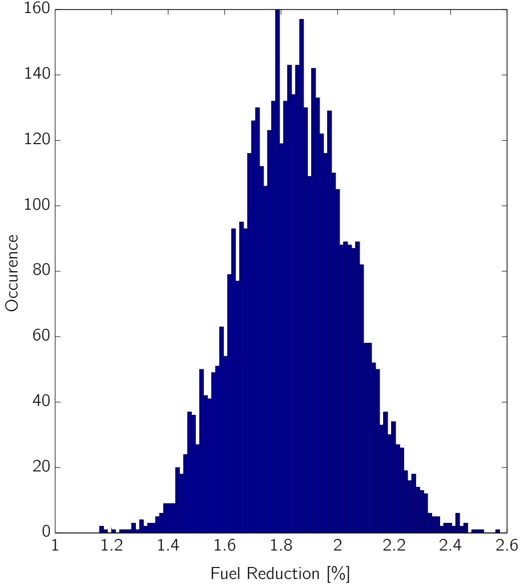
Algorithm: Savings calculation for two HDVs

$N_s \leftarrow s$; $Best \leftarrow D(s, d_1) + D(s, d_2)$;
$m_i \leftarrow 0\ \forall i$;
for ν *in* V **do**
    if $((2-\eta)D(s,\nu) + D(\nu, d_1) + D(\nu, d_2) < Best)$ *&*
    $(D(s,\nu) + D(\nu, d_1) \leq D(s, d_1) + m_1)$ *&*
    $(D(s,\nu) + D(\nu, d_2) \leq D(s, d_2) + m_2)$ **then**
        $N_s \leftarrow \nu$;
        $Best \leftarrow (2-\eta)D(s,\nu) + D(\nu, d_1) + D(\nu, d_2)$;
        Update m_1 or m_2 if needed;
    end
end
$Savings = D(s, d_1) + D(s, d_2) - Best$;

Savings

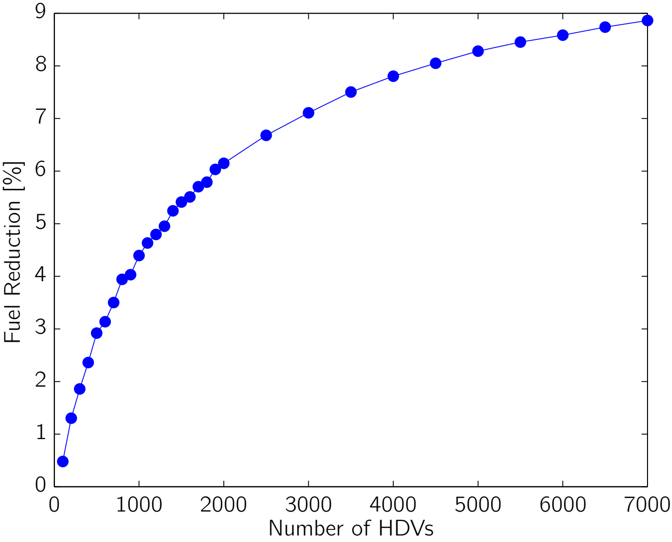


Savings



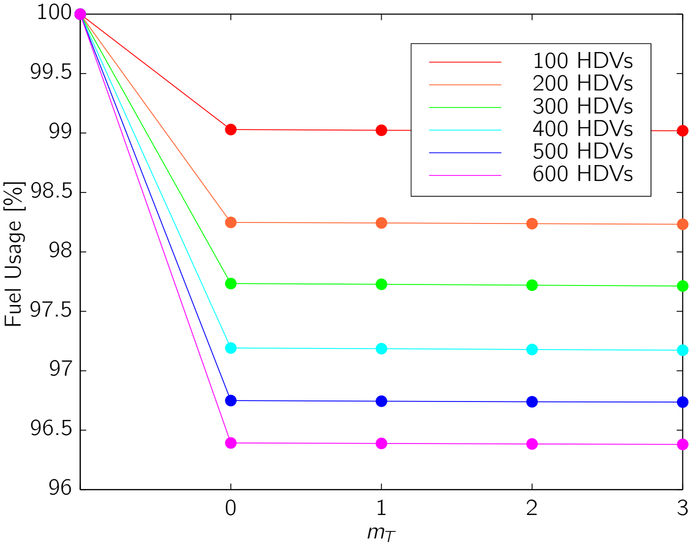
160
140
120
100
80
60
40
20
0
Occurence
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
Fuel Reduction [%]

Savings



Fuel Reduction [%]
0
1
2
3
4
5
6
7
8
9
0
1000
2000
3000
4000
5000
6000
7000
Number of HDVs

Increasing Possible Detours



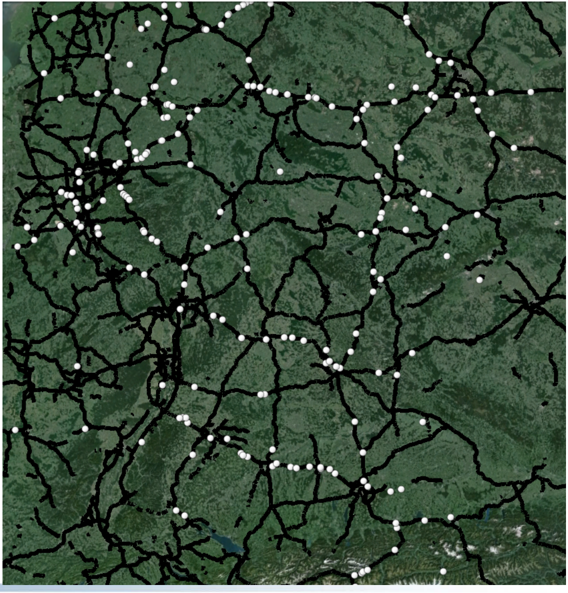
Conclusion & Current Work

It is possible to reduce fuel use by 5%
when coordinating 1000 HDVs on the German Autobahn.

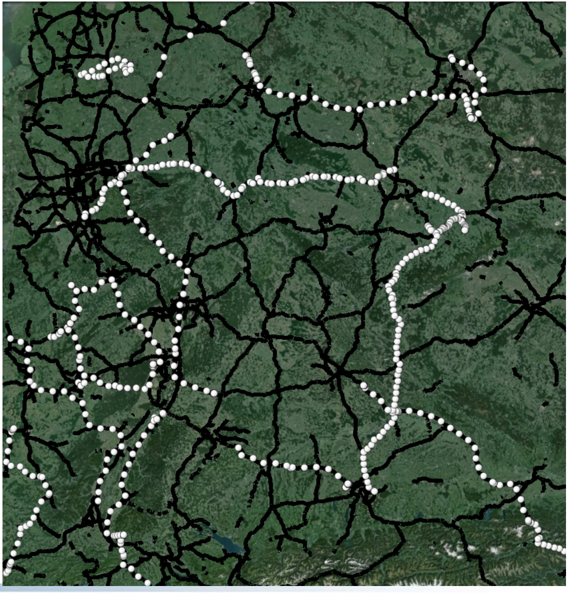
Work is ongoing:

- Platooning when traffic is time dependent
- Accounting for breaks and legal requirements
- Continue with real-world experiments

Real-world Data



Real-world Data



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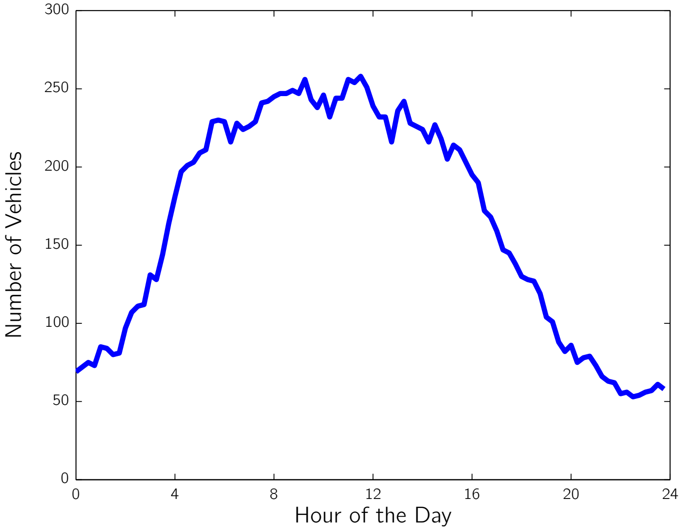

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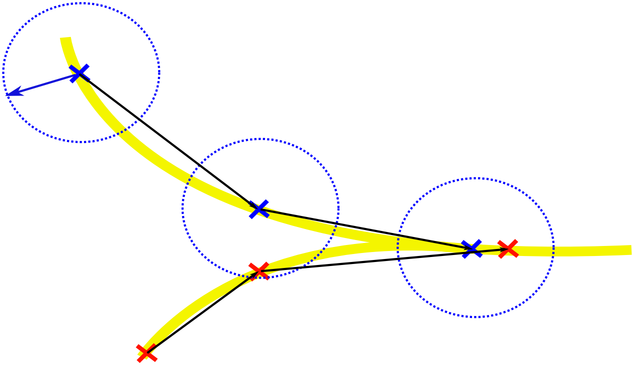

Real-world Data

- $r = 0.2$ km
  - 78 out of 875 vehicles platooned at least once during the day.
  - 0.16% of total fuel saved by the platooned vehicles.
  - 585 km platooning out of total 403,413 km driven.

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- $r = 1$ km
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- $r = 1$ km
  - 241 out of 875 vehicles platooned at least once during the day.
  - 0.38% of total fuel saved by the platooned vehicles.
  - 4,369 km platooning.

- $r = 5$ km
  - 778 out of 875 vehicles platooned at least once during the day.
  - 1.2% of total fuel saved by the platooned vehicles.
  - 43,325 km platooning.

Recent Grant

COMPANION EU Project: Cooperative Dynamic Formation of Platoons for Safe and Energy-optimized Goods Transportation

Scania, Volkswagen, KTH, OFFIS, IDIADA, S&T AS, Transportes Cerezuela

Pause

Questions?

Outline

Heavy-duty Vehicle Platooning

Sports Scheduling

Handball

Handball

Handball

Handball

Elitserien – Top Level of Swedish Handball

- 14-team league; owners want more than 26 games, but not 39
- Form 2 divisions which hold a single round-robin tournament
- Has standard requirements, so hopefully the results are useful
- Want a very fair home-away patterns in their schedule
- Desire a template which they can use on their own

Template

0	-2	3	-4	5	-6	7	-8	9	-5	6	-7	10	-11	12	-13	4	-14	2	-3	...
-7	1	0	-3	4	-5	6	-9	7	-12	10	-6	5	-4	11	-14	13	3	-1	8	...
-6	7	-1	2	0	-4	5	-10	8	-7	9	-5	11	-13	6	-12	14	-2	4	1	...
-5	6	-7	1	-2	3	0	-11	10	-6	5	-13	12	2	-14	8	-1	9	-3	7	...
4	0	-6	7	-1	2	-3	13	-14	1	-4	3	-2	8	-7	9	-10	-11	6	-12	...
3	-4	5	0	-7	1	-2	12	-13	4	-1	2	-8	14	-3	7	-9	10	-5	-11	...
2	-3	4	-5	6	0	-1	14	-2	3	-8	1	-9	-10	5	-6	11	-12	13	-4	...

0	9	-10	11	-12	13	-14	1	-3	-9	7	-11	6	-5	10	-4	12	-13	14	-2	...
14	-8	0	10	-11	12	-13	2	-1	8	-3	-10	7	-12	13	-5	6	-4	11	-14	...
13	-14	8	-9	0	11	-12	3	-4	14	-2	9	-1	7	-8	-11	5	-6	12	-13	...
12	-13	14	-8	9	-10	0	4	-12	13	-14	8	-3	1	-2	10	-7	5	-9	6	...
-11	0	13	-14	8	-9	10	-6	11	2	-13	14	-4	9	-1	3	-8	7	-10	5	...
-10	11	-12	0	14	-8	9	-5	6	-11	12	4	-14	3	-9	1	-2	8	-7	10	...
-9	10	-11	12	-13	0	8	-7	5	-10	11	-12	13	-6	4	2	-3	1	-8	9	...

Home/Away Pattern Sets

- General scheduling is very hard
- A common simplifying method involves constructing home/away pattern (HAP) sets
- Desirable home-away patterns for each team

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Team 1	AHAHA
Team 2	AAHAH
Team 3	AHHAH
Team 4	HAHAH
Team 5	HHAHA
Team 6	HAAHA

Home/Away Pattern Sets

- General scheduling is very hard
- A common simplifying method involves constructing home/away pattern (HAP) sets
- Desirable home-away patterns for each team

Team 1	AHAHA
Team 2	AAHAH
Team 3	AHHAH
Team 4	HAHAH
Team 5	HHAHA
Team 6	HAAHA

But not every HAP set is schedulable

List of Requirements

1. Each 7-team division must hold a SRRT to start the season.
2. This must be followed by two SRRTs between the entire league, the second SRRT being a mirror of the first.
3. There must be a minimum number of breaks in the schedule.
4. Each team has one bye during the season (to occur during the divisional RRT).
5. At no point during the season can the number of home and away games played by a team differ by more than 1.
6. Any pair of teams must have consecutive meetings occur at different venues. (AVR)
7. Each division must have 3 pairs of complementary schedules.

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2. If you end the first SRRT: away at team 1 and home for team 2, you start the next SRRT: away at team 2 and home for team 1
3. There must be a minimum number of breaks in the schedule.
4. Each team has one bye during the season (to occur during the divisional RRT).
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1. Each 7-team division must hold a SRRT to start the season.
2. This must be followed by two SRRTs between the entire league, the second SRRT being a mirror of the first.
3. We don't want "HH" or "AA"
4. Each team has one bye during the season (to occur during the divisional RRT).
5. At no point during the season can the number of home and away games played by a team differ by more than 1.
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2. This must be followed by two SRRTs between the entire league, the second SRRT being a mirror of the first.
3. There must be a minimum number of breaks in the schedule.
4. Each division has an odd number of teams
5. At no point during the season can the number of home and away games played by a team differ by more than 1.
6. Any pair of teams must have consecutive meetings occur at different venues. (AVR)
7. Each division must have 3 pairs of complementary schedules.

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3. There must be a minimum number of breaks in the schedule.
4. Each team has one bye during the season (to occur during the divisional RRT).
5. Can't start "AHAAH"
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4. Each team has one bye during the season (to occur during the divisional RRT).
5. At no point during the season can the number of home and away games played by a team differ by more than 1.
6. Teams meeting 3 times: “AHA” or “HAH” (not “AAH” or ”HHA”)
7. Each division must have 3 pairs of complementary schedules.

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7. A H A H B A H A H A H A H H A H A H A H . . .
   H A H B A H A H A H A H A A H A H A H A . . .

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Previous Results

Two results from the literature apply

- Every n-team RRT, n even, must have at least $n-2$ breaks, DeWerra (1981)
- For an n-team RRT, n odd, there exists a unique no break tournament, Frončec (2005)

Previous Results

BAHAHAH	
HBAHAHA	AHAHAHAHAHAHA
AHBAHAH	AHAHAHAHAHAHH
HAHBAHA	AHAHAHAHAHHAH
AHAHBAH	AHAHAHAHHAHAH
HAHAHBA	AHAHAHHAHAHAH
AHAHAHB	AHAHHAHAHAHAH
or	AHHAHAHAHAHAH
BHAHAHA	HAAHAHAHAHAHA
ABHAHAH	HAHAAHAHAHAHA
HABHAHA	HAHAHAAHAHAHA
AHABHAH	HAHAHAHAAHAHA
HAHABHA	HAHAHAHAHAAHA
AHAHABH	HAHAHAHAHAHAA
HAHAHAB	HAHAHAHAHAHAH

Constructing HAP Sets

B H A H A H A	H A H $\boxed{\text{A A}}$ H A H A H A H A	...
H A B H A H A	H A H A H A H $\boxed{\text{A A}}$ H A H A	...
H A H A B H A	H $\boxed{\text{A A}}$ H A H A H A H A H A	...
H A H A H A B	H A H A H A H A H $\boxed{\text{A A}}$ H A	...
A B H A H A H	A H A H A H A $\boxed{\text{H H}}$ A H A H	...
A H A B H A H	A $\boxed{\text{H H}}$ A H A H A H A H A H	...
A H A H A B H	A H A H A H A H A $\boxed{\text{H H}}$ A H	...
B A H A H A H	A H A H A H A H A H A $\boxed{\text{H H}}$	...
A H B A H A H	A H A $\boxed{\text{H H}}$ A H A H A H A H	...
A H A H B A H	A H A H A H A H A H A H A	...
A H A H A H B	A H A H A $\boxed{\text{H H}}$ A H A H A H	...
H B A H A H A	H A H A H $\boxed{\text{A A}}$ H A H A H A	...
H A H B A H A	H A H A H A H A H A H $\boxed{\text{A A}}$	...
H A H A H B A	H A H A H A H A H A H A H	...

Constraints

1. Each 7-team division must hold a SRRT to start the season.
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3. There must be a minimum number of breaks in the schedule.
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7. Each division must have 3 pairs of complementary schedules.

Counting HAP Sets

Proposition

For an n-team tournament, $\frac{n}{2}$ odd, with a divisional RRT before full-league DRRT, there are

$$
{}_{\frac{n}{2}}P_{\frac{n-2}{4}} \times \left(\frac{n+2}{4}\right)^3 \times \frac{n-2}{4}!
$$

unique HAP sets satisfying the requirements, except possibly for the AVR, with $\frac{n-2}{4}$ pairs of complementary schedules within each division.

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unique HAP sets satisfying the requirements, except possibly for the AVR, with $\frac{n-2}{4}$ pairs of complementary schedules within each division.

For the 14-team Elitserien, this is 80640 HAP sets.

Example Violating AVR

By construction, every HAP Set can be scheduled in a manner satisfying the League Requirements, except possibly for the AVR.

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By construction, every HAP Set can be scheduled in a manner satisfying the League Requirements, except possibly for the AVR.

$$\begin{array}{ccccccc||ccccccccccccc}
H & A & H & B & \boxed{A} & H & A & H & A & H & A & H & A & H & A & H & A & H & A & \boxed{A} \\
H & A & H & A & \boxed{H} & B & A & H & A & H & A & H & A & H & A & H & A & H & A & \boxed{H}
\end{array}$$

Simple Condition

For an arbitrary HAP set S, define

$$S(t,p) = \begin{cases} H: \text{if team } t \text{ plays home in period } p, \\ A: \text{if team } t \text{ plays away in period } p, \\ B: \text{if team } t \text{ has a bye in period } p. \end{cases}$$

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Proposition

For a HAP set S to be schedulable, for any two teams t_1 and t_2 in the same division, there must be two periods p_1 in Part I and p_2 in Part II such that

$$S(t_1, p_1) = H \text{ and } S(t_2, p_1) = A,$$
$$S(t_1, p_2) = A \text{ and } S(t_2, p_2) = H.$$

Efficiency of Simple Test

n	HAP sets	HAP removed by simple condition	% removed
6	24	8 (of 20 unschedulable)	40%
10	1080	396 (of 998 unschedulable)	$\approx$ 40%
14	80640	30720 (of 79024 unschedulable)	$\approx$ 39%

Another Necessary Condition

B	A	H	A	H	A	H	A	H	A	H	A	H	A	H	A	H	A	H	$\boxed{H}$
A	H	B	A	H	A	H	A	H	A	H	H	A	H	A	H	A	H	A	H
A	H	A	H	B	A	H	A	H	A	H	A	H	A	H	A	H	A	H	$\boxed{A}$

Another Necessary Condition

- Check if i or j is already "committed" to play another team in every period when they could possibly meet.
  - For example, if i can only play j in periods p_1 or p_2
  - i must play k_1 in p_1
  - j must play k_2 in p_2
- This is only slightly more expensive computationally to check than the simple condition, but it catches many "deeper" contradictions.
- This condition removes 46944 of the 80640 HAP sets (59%).

Latin Square Example

Team 1	AHAHA
Team 2	AAHAH
Team 3	AHHAH
Team 4	HAHAH
Team 5	HHAHA
Team 6	HAAHA

Latin Square Example

Team 1	AHAHA
Team 2	AAHAH
Team 3	AHHAH
Team 4	HAHAH
Team 5	HHAHA
Team 6	HAAHA

	1	2	3	4	5	6
1						
2	[2,3,4,5]					
3	[3,4,5]	[2]				
4	[1,2,3,4,5]	[1]	[1,2]			
5	[1]	[1,2,3,4,5]	[1,3,4,5]	[2,3,4,5]		
6	[1,2]	[1,3,4,5]	[1,2,3,4,5]	[3,4,5]	[2]	

Efficiency of the Latin Square Approach

n	HAP sets	HAP removed by L.S. condition	% removed
6	24	20 (of 20 unschedulable)	100%
10	1080	998 (of 998 unschedulable)	100%
14	80640	75995 (of 79024 unschedulable)	$\approx 96\%$

Efficiency of the Latin Square Approach

n	HAP sets	HAP removed by L.S. condition	% removed
6	24	20 (of 20 unschedulable)	100%
10	1080	998 (of 998 unschedulable)	100%
14	80640	75995 (of 79024 unschedulable)	$\approx$ 96%

n	HAP sets	HAP removed "one pass"	% removed
6	24	10 (of 20 unschedulable)	50%
10	1080	504 (of 998 unschedulable)	$\approx$ 51%
14	80640	51946 (of 79024 unschedulable)	$\approx$ 66%

Final Template

0	-2	3	-4	5	-6	7	-8	9	-5	6	-7	10	-11	12	-13	4	-14	2	-3	...
-7	1	0	-3	4	-5	6	-9	7	-12	10	-6	5	-4	11	-14	13	3	-1	8	...
-6	7	-1	2	0	-4	5	-10	8	-7	9	-5	11	-13	6	-12	14	-2	4	1	...
-5	6	-7	1	-2	3	0	-11	10	-6	5	-13	12	2	-14	8	-1	9	-3	7	...
4	0	-6	7	-1	2	-3	13	-14	1	-4	3	-2	8	-7	9	-10	-11	6	-12	...
3	-4	5	0	-7	1	-2	12	-13	4	-1	2	-8	14	-3	7	-9	10	-5	-11	...
2	-3	4	-5	6	0	-1	14	-2	3	-8	1	-9	-10	5	-6	11	-12	13	-4	...

0	9	-10	11	-12	13	-14	1	-3	-9	7	-11	6	-5	10	-4	12	-13	14	-2	...
14	-8	0	10	-11	12	-13	2	-1	8	-3	-10	7	-12	13	-5	6	-4	11	-14	...
13	-14	8	-9	0	11	-12	3	-4	14	-2	9	-1	7	-8	-11	5	-6	12	-13	...
12	-13	14	-8	9	-10	0	4	-12	13	-14	8	-3	1	-2	10	-7	5	-9	6	...
-11	0	13	-14	8	-9	10	-6	11	2	-13	14	-4	9	-1	3	-8	7	-10	5	...
-10	11	-12	0	14	-8	9	-5	6	-11	12	4	-14	3	-9	1	-2	8	-7	10	...
-9	10	-11	12	-13	0	8	-7	5	-10	11	-12	13	-6	4	2	-3	1	-8	9	...

Additional Desires

Additional requests and concerns can be addressed when assigning teams to numbers:

- Venue availabilities
- Desired derby games
- More meetings between the top teams and between the bottom teams in the last weeks.

Summary

- We constructed (and counted) HAP sets with a minimum number of breaks
- We are able to remove many HAP sets as unschedulable with respect to the AVR
- We can then construct a template which can be agreed upon by the league owners
- We assign teams to numbers to construct a yearly schedule

Conclusion

We talked about:

- Vehicle Platooning
- Sports Scheduling

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- Vehicle Platooning
- Sports Scheduling

We could have also talked about:

- DFO and Particle Accelerator Design
- Tiled QR Factorization
- Mathematics Outreach
- Optimizing the Movement of Coordinated Agents
- Non-Traditional Auctions
- Radiation Vault Design

Thank you for your time!

Questions?

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